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Effect of slope position on soil properties and soil moisture regime of Stagnosol in the vineyard

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Abstract: Hillslope hydrology in agricultural landscapes is complex due to a variety of hydropedological processes and field management possibilities. The aim was to test if there are any differences in soil properties and water regime along the hillslope and to compare vineyard rows (vine) with inter-rows (grass) area for those properties. The study determined that there are significant differences in the contents of soil particle fractions, pH, and humus content along the slope ($P < 0.0001$), with lower confidence level in bulk density ($P < 0.05$). Differences between row and inter-row space were significant for the pH, humus, and silt content, but for sand and clay content, and bulk density differences were not determined. The study determined differences in soil water content among five slope positions ($P < 0.0001$), and between row and inter-row vineyard space (all with $P < 0.05$). Where in the upper slope positions (e. g., P1) soil water content was higher than on lower slope positions. Higher soil water content was observed at higher slope positions, associated with clay content. However, it can be concluded that the retention of moisture on the slope is more influenced by local-scale soil properties (primarily soil texture) and variability of the crop (row/inter-row) than the position on the slope.

Keywords: Hillslope; Agriculture; Stagnosol; Soil properties; Soil water content; Bg horizon.

INTRODUCTION

As a major topographical parameter, the slope position, i.e., the relative height position along the hillslope, has a significant indirect influence on the soil physicochemical properties by controlling the movement of water and eroded material in a hillslope and contributing to the spatial differences of the soil properties (Begum et al., 2010; Khormail et al., 2007). The hillslope erosion process influences the physical, chemical, and biological properties of soil's upper horizons. Changes in slope inclination, have a major impact on soil erosion, which is an important disturbance and causes significant loss of finer soil particles (Carroll et al., 2000). This kind of processes are rarely uniform, and often forms a spatial variability along the slope in the topsoil layer. For instance, Wang et al. (2001) regarded topography as the dominant factor influencing soil property variation due to its influence on runoff, drainage, microclimate, and soil erosion. Moreover, many soil properties including particle-size distribution, pH, and organic matter content vary substantially with the slope position (Mulugeta and Sheleme, 2010; Wang et al., 2001).

Numerous studies, focused on the hillslope hydropedology, exposed the dependence of various soil properties on terrain characteristics, e.g., depth of topsoil horizon (Mayer et al., 2019; Sarapatka et al., 2018; Zádorová et al., 2011; Ziadat et al., 2010), organic carbon content (Jakšík et al., 2015; Mayer et al., 2019; Sarapatka et al., 2018), water content (Jakšík et al., 2015; Romano and Palladino, 2002) as presented in Nikodem et al. (2021). In the agricultural landscapes the tillage erosion is additionally combined with the water erosion during surface runoff.

Erosion-induced profile truncation occurs mostly in the arable soil landscapes at upper soil slope positions where, the removal of topsoil due to a combined effect of water and tillage erosion leads to a reduction in soil surface elevation with soil tillage operations performed at a constant tool i.e., plough depth, resulting in gradual penetration of the upper parts of the subsoil horizons (Świtoniak, 2014; Wiaux et al., 2014). As a result of soil erosion, the C horizon can be found at varying soil depths from directly at the surface to practically down to > 1.5 m (Deumlich et al., 2010). Other soil horizons, if not removed by erosion (e.g., E and Bt), can vary greatly in thickness and properties depending on the profile truncation and the particular hillslope position in the landscape (Herbrich et al., 2017; Rieckh et al., 2012).

Another important parameter directly connected to soil properties (Hu and Si, 2014), soil moisture content, varies spatially, which is affected by the climate (e.g., Zhao et al., 2016), land use/vegetation (Gerrits et al., 2010; Liang et al., 2014; Zhu and Shao, 2008) and topography (Famiglietti et al., 1998; Western et al., 2004). Thus, the uniformity of soil physical properties and soil moisture distribution are essential for agricultural crops. Soil physical properties essentially regulate the potential volume of soil that affects plant roots growth and distribution, soil water availability, root respiration, and exchange of soil oxygen (Lanyon et al., 2004).

Plants can also affect soil moisture distributions and the soil hydraulic properties either directly by root water uptake and accumulating water inside the root biomass, or more indirectly by modifying the soil structure and porosity through the growing root system (e.g., Kodešová et al., 2006; Rasse et al., 2000).

In addition to topography, vegetation (Gómez-Plaza et al., 2000), parent material, heterogeneity of organic matter content and variability of soil texture, and soil structure (Kodešová et al., 2009) plays an important role in the spatial variability of soil moisture.

Focusing on agricultural hillslope areas, majority of the vineyards are located on the slope. Croatia has ~22 000 ha of vineyards (FAO, 2021), and the large proportion of them are intensively managed on relatively steep slopes. In vineyards, the quality of the soil is a key factor determining grape quality (van Leeuwen et al., 2009), which is often difficult to maintain due to erosion processes. Rodrigo-Comino et al. (2017) showed an example of sloping vineyards in a Mediterranean environment with bare soils that are associated with high soil losses and an uneven spatiotemporal distribution of hydrological and geomorphological processes. The difficulty of quantifying hillslope hydrology water balance in vineyard is the fact that there are two very different types of vegetation i.e., vine and grass, in addition to different management of inter-row and row areas. Since the inter-row part of the vineyard usually grass-covered and occasionally cultivated, the soil properties in the row are different from those in the inter-row space of the vineyard. Thus, some authors noted different values of bulk density (e.g., Bogunović et. al., 2016; Hendgen et., al., 2020), soil organic carbon, and plant available water (Hendgen et. al., 2020) between the row and inter-row spaces.

Pseudogleys (Stagnosols according to WRB 2014) represent the second most widespread soil type in Croatia, developed almost exclusively in its Pannonian region (Husnjak, 2014; Rubinić et al., 2015). Although 55% of Croatian Stagnosols are found on agricultural land or in agroecosystems (Husnjak et al., 2011), they usually have numerous constraints for agricultural production. Primarily, this is due to their unfavorable water/air regime (precipitation water periodically stagnates on/in the poorly permeable subsoil horizon). Bogunović et al. (2018) studied various tillage systems e.g., conventional, no-till and deep tillage on Stagnosols where they found a direct link between tillage type and physical soil properties which influenced soil erodibility.

To improve our understanding of water flow and retention on arable sloping soils, it is extremely important to know the origin of the variability of soil properties along and across the slope. Therefore, the aim of this study was to determine if there are any differences in Stagnosol properties among different points along the slope between row (vine root) and inter-row (gras-covered) vineyards areas. In addition, we aimed to compare the soil moisture regime in the vineyard row (vine root) and grass-covered inter-row area, in order to investigate the influence of roots (vine-grasses) on soil water content.

MATERIALS AND METHODS

Study site description

The study was performed during 2019 in a vineyard near Jastrebarsko (Croatia) (45°41'22" N; 15°38'22" E) (Figure 1). The average annual rainfall at the investigated area is 989 mm, while the average annual air temperature is 10.6 °C. The investigated plot is located on the slope of the southeastern exposure, 90 m long, with a slope of 15%, and the rows are oriented downslope (Figure 1B). A vineyard was planted on the investigated plot in 1999, with the Traminac cv. grafted on the Kober 5BB rootstock. The planting distance between the vines in a row are 1.0 m, while the distance between the rows is 2.5 m. The vineyard has the interrow area covered with grass. In the vineyard, shallow surface tillage (~ 25 – 30 cm depth) is carried out every autumn, every other year in every second row, while in the vegetation period the vineyard is maintained by mowing the grass.

Field study

The dominant soil type at the study site is Stagnosol. Along the slope, five sampling points have been selected, which are marked as P1, P2, P3, P4, and P5. Soil at selected slope points (P1–P5) were classified according to IUSS Working Group WRB (2015) as follows: Eutric Protovertic Stagnosol (Aric, Inclinic, Loamic), Eutric Protovertic Stagnosol (Aric, Endoclayic, Epiloamic, Inclinic), Dystric Protovertic Stagnosol (Aric, Colluvic, Inclinic, Loamic), Dystric Stagnosol (Aric, Colluvic, Inclinic, Loamic), Dystric Stagnosol (Aric, Colluvic, Inclinic, Sitltic), respectively. The parent material of investigated site was loess-like sediment, i. e. loess derivate (Rubinić et. al., 2018). Before digging the soil profile at each of the five slope points a preliminary survey was conducted. The aim of the preliminary survey was to determine the homogeneity / heterogeneity of soil properties by isohypses at five selected slope points. In this research, we did not perform any measurements at the

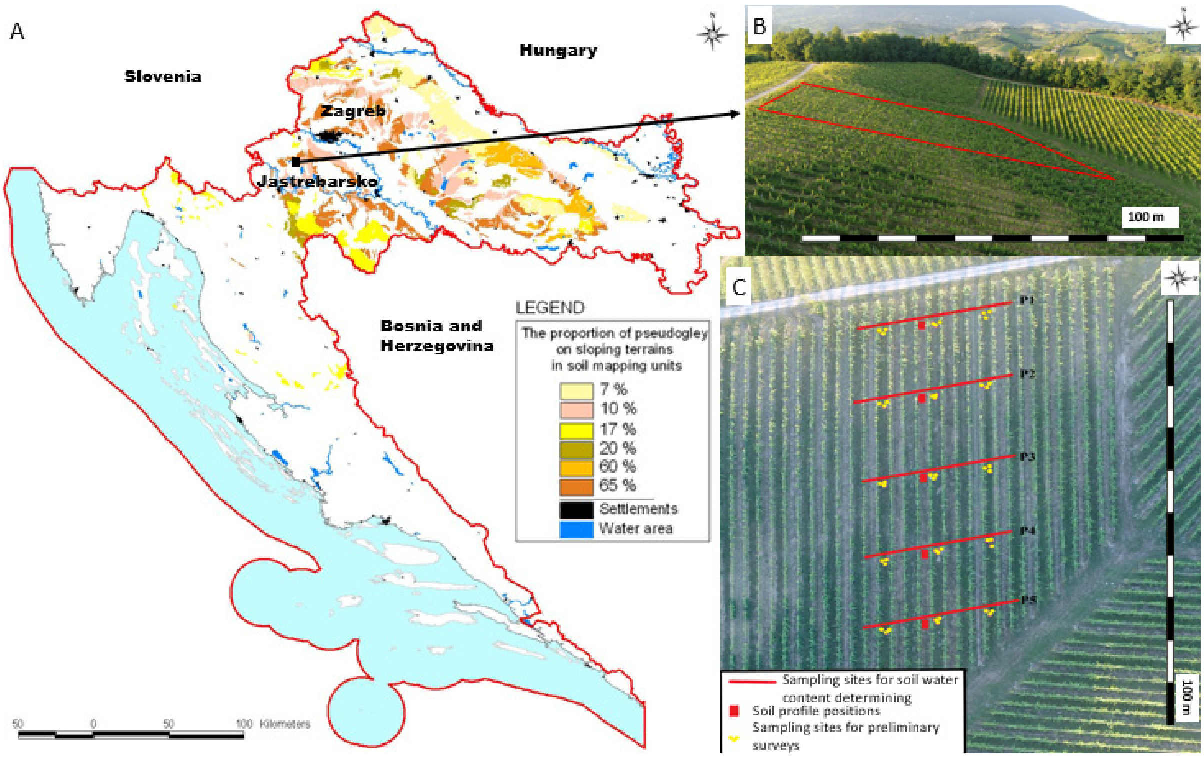

Fig. 1. Map showing the proportion of Stagnosol (Pseudogley) in Croatia (Husnjak, 2014) (A) and the specific location of the study site (i.e., investigated plot orientation (B) and scheme of sampling sites (C)).

hilltop or hill bottom as the vineyard rows do not extend to those positions. Crop planting and management were on of the main factors determining the water dynamics in the upper soil horizons, thus we focused our research on the vineyard area (Figure 1B, 1C). Thus, at five selected positions (points) along the slope in three inter-row spaces, soil sampling was performed with a Holland auger at depths 0–40; 40–80 and 80–110 cm. Therefore, 45 soil samples were taken for preliminary tests. The sampling scheme for preliminary survey is shown in Figure 1C. The soil sampling points on the slope were equidistant from each other (18 m) along the entire length of the slope. For the purpose of determining the soil properties, on the selected slope positions five pedological profiles were dug up to a depth of 1.1 m (Figure 2). The profiles were described in detail based on the FAO (2006) and/or Schoeneberger et al. (2012). Soil samples were taken in the disturbed and undisturbed state in the inter-row area of vineyard. Undisturbed soil samples were taken in triplicate in 100 cm^3 cylinders from 30 and 90 cm depths at all slope points (P1–P5) and in row and inter-row space. Disturbed soil samples were taken along entire depth of each soil horizon in the plastic bags. Altogether, 60 samples in undisturbed (30 in row, and 30 in inter-row space) and 60 samples in disturbed state (30 in row, and 30 in inter-row space) were collected. Sampling during 2019 to determine soil moisture content (and determine soil properties) was carried out in the inter-row spaces cultivated in autumn of 2017.

During the study period (2019), the soil was not cultivated but only maintained by mowing the inter-row space of the vineyards, while the row area was treated with herbicides. Field research for determining soil moisture content was conducted during 2019, 1–2 times a month (a total of 13 times), while soil samplings were performed on the same topographical position where soil profiles were dug out.

Soil samples used for determination of the gravimetric soil water content were sampled each time in the adjacent row and inter-row space, so a total of 13 rows, and 13 inter-rows of vineyard, also at 30 and 90 cm depth. Soil samples used for determination of the current soil water content were samples in the disturbed state with a Holland auger, along the slope at two depths (30 and 90 cm), in rows and inter-rows of vineyard in three replications (a total of 60 samples in one sampling). Soil samples for gravimetric determination of soil moisture were placed in pre-labeled glass bottles, which were tightly closed to prevent moisture evaporation.

Laboratory methods

All disturbed soil samples were air-dried. A portion of each sample was crushed and sieved through a 2 mm sieve. Soil particle size distribution was determined using the pipette-method, with wet sieving and sedimentation after dispersion with sodium-pyrophosphate ($Na_4P_2O_7$, c = 0.4 M, Gee and Or, 2002). Soil pH in H_2O was determined in 1:2.5 suspensions HRN ISO 10390:2005. Humus content was obtained by Tjurin method, by acid-dichromate ($K_2Cr_2O_7$, c = 0.4 M) digestion (JDPZ, 1966). Bulk density was determined according to Grossman and Reinsch (2002). Soil water retention at 0.33–15.0 bar was obtained according to Dane and Hopmans (2002)

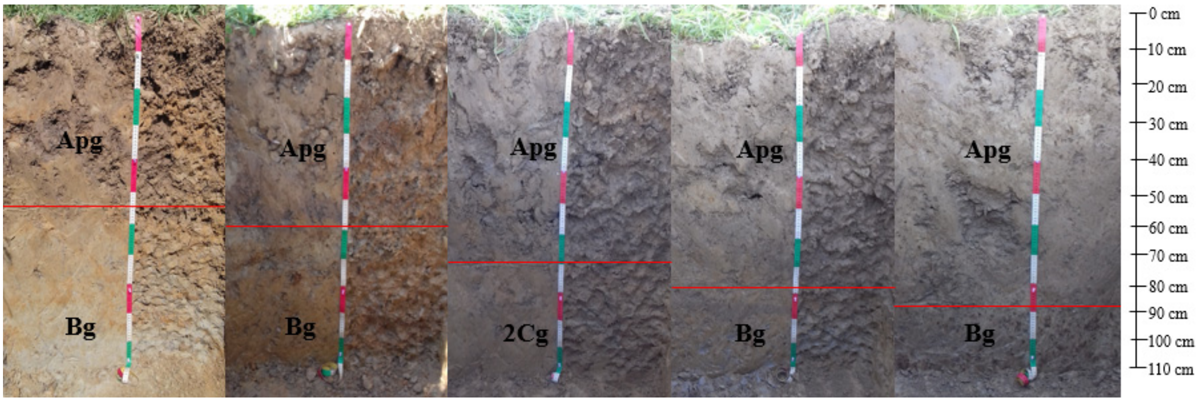

Fig. 2. Soil profiles along slope at different positions in the interrow area: P1, P2, P3, P4, P5. Red line indicates the Ap/Bg or 2Cg horizon boundary. The sunlight affected the visual representation of the soil profile images, so the color of the soil in dry state was determines using the Munsell chart and shown in Table 4.

Table 1. Average values (from tree inter-rows) and coefficient of variations (CV) for soil properties at five slope positions (P1–P5).

Position	Depth (cm)	Sand average* (CV)	Silt average* (CV)	Clay average* (CV)	pH (H_2O) average* (CV)	Humus average* (CV)
P1	0–40	4.43 (6.89)	58.04 (0.75)	37.53 (0.45)	5.33 (0.56)	1.80 (1.79)
	40–80	3.60 (10.02)	60.20 (0.10)	36.20 (0.44)	5.52 (0.46)	1.33 (2.50)
	80–110	3.67 (8.33)	63.73 (0.12)	32.60 (0.40)	5.81 (0.46)	0.78 (5.70)
P2	0–40	9.53 (2.64)	56.10 (0.26)	34.37 (0.35)	5.12 (0.52)	1.89 (2.75)
	40–80	10.27 (0.56)	54.63 (0.21)	35.10 (0.20)	5.24 (0.69)	1.04 (5.08)
	80–110	12.23 (4.93)	42.54 (0.55)	45.23 (0.31)	5.61 (0.36)	0.80 (3.39)
P3	0–40	13.90 (1.44)	53.60 (0.00)	32.50 (0.20)	4.75 (0.63)	2.05 (2.68)
	40–80	11.70 (3.56)	51. 60(0.62)	36.70 (0.46)	5.11 (0.30)	1. 97 (0.72)
	80–110	31.30 (0.96)	40.43 (0.49)	28.27 (0.31)	5.20 (0.38)	1.54 (3.37)
P4	0–40	10.50 (2.86)	61.97 (0.32)	27.53 (0.12)	5.46 (0.74)	2.28 (3.42)
	40–80	11.80 (1.69)	63.90 (0.35)	24.30 (0.40)	5.03 (0.80)	2.34 (1.69)
	80–110	11.13 (2.07)	64.40 (0.62)	24.47 (0.40)	5.19 (0.29)	1.27 (5.69)
P5	0–40	10.87 (2.32)	63.06 (0.58)	26 07 (0.40)	4.95 (0.81)	2.87 (1.48)
	40–80	10.47 (2.92)	62.96 (0.67)	26.57 (0.40)	5.12 (11.45)	1.42 (2.46)
	80–110	8.57 (4.72)	64.23 (0.32)	27.20 (0.30)	5.38 (0.47)	1.01 (2.20)

on pressure plate extractor. Soil physical and chemical properties of investigated soil are summarized in Table 1. The soil water content was determined by the gravimetric method. The gravimetric water content was obtained by drying the soil samples (at disturbed state) at 105 ºC to constant mass. The soil water content was determined by calculation,

$$\%soil\ water = \frac{weight\ of\ wet\ soil(g) - weight\ of\ dry\ soil\ at\ 105°C(g)}{weight\ of\ dry\ soil\ at\ 105°C(g)} \times 100[mass\ \%]. \quad (1)$$

Since soil samples were taken in the disturbed state, each of the obtained soil water content values was multiplied by the bulk density of the soil at the corresponding sampling site so that the results of the soil water content could be expressed in vol %.

Meteorological data (i.e., precipitation) for 2019 was taken from National hydrometeorological department for meteo station Goli vrh, the nearest meteorological station of investigated location.

Data analysis

In the preliminary study, the homogeneity / heterogeneity of analyzed soil properties at five sampling points by isohypses was estimated using coefficient of variation (CV). To test the effects of position along the slope (P1–P5), row spacing (row / inter-row) and their interaction on the soil properties and soil water content, two-way analysis of variance (ANOVA) was performed. Means of levels of predictors that were found statistically significant at the alpha level of $P = 0.05$ were compared using the Bonferroni correction with alpha set at $P = 0.05$. In cases where the interaction was found significant ($P < 0.05$), multiple comparisons were performed only between positions within the same row spacing (slice). The analyses were performed separately for each of the two horizons. All statistical analyses were performed in R 3.3.2 (R Core Team, 2016) in RStudio 1.1.423 (RStudio Team, 2016).

RESULTS AND DISCUSSION

Soil properties along the hillslope

The coefficients of variation (CV) of the soil properties analyzed in the preliminary survey to are shown in Table 1. The CV values for most properties at most positions are below 2.00, except for the sand content at position P1 (40–80 cm) where CV 10.02, and the pH reaction of the soil at position P4 (80–100 cm) where CV is 11.45. Considering the CV values at individual positions, it can be concluded that the heterogeneity of soils by isohypses is sufficiently small to allow for the generalization of following results on the entire slope area. The depth of the surface Apg horizon increases from the top to the bottom of the slope, which is associated with soil erosion/deposition. Numerous authors confirm similar results (e.g., Mulugeta and Sheleme, 2010; Ziadat et al., 2010).

The results of soil texture analysis indicate that there are significant differences in the content of individual soil particle fractions by position along the slope and between the row and inter-row spacing of vineyard (Table 2). Thus, the content of sand, silt, and clay differ significantly for the position on the slope ($P < 0.0001$). There were also differences in the average sand content between the row and the inter-row spacing for the subsurface horizon ($P < 0.0001$) where on average a higher sand content was observed in the inter-row spacing compared to the row space. The difference in sand content between the row and the inter-row space was not observed in the Apg horizon (Figure 3A).

The silt content also differs significantly depending on the position on the slope ($P < 0.0001$) where the highest average silt content was observed at the P5 position, while the lowest average silt content was at the P2 and P3 slope positions. Differences in the average silt content were observed both between the row and the row spacing both in the Apg ($P = 0.0216$) and in the subsurface horizon ($P < 0.0001$), where the average higher silt content was in the row compared to the inter-row spacing (in both horizons) (Figure 3B).

The clay content also differed significantly depending on the position on the slope ($P < 0.0001$), where significantly the

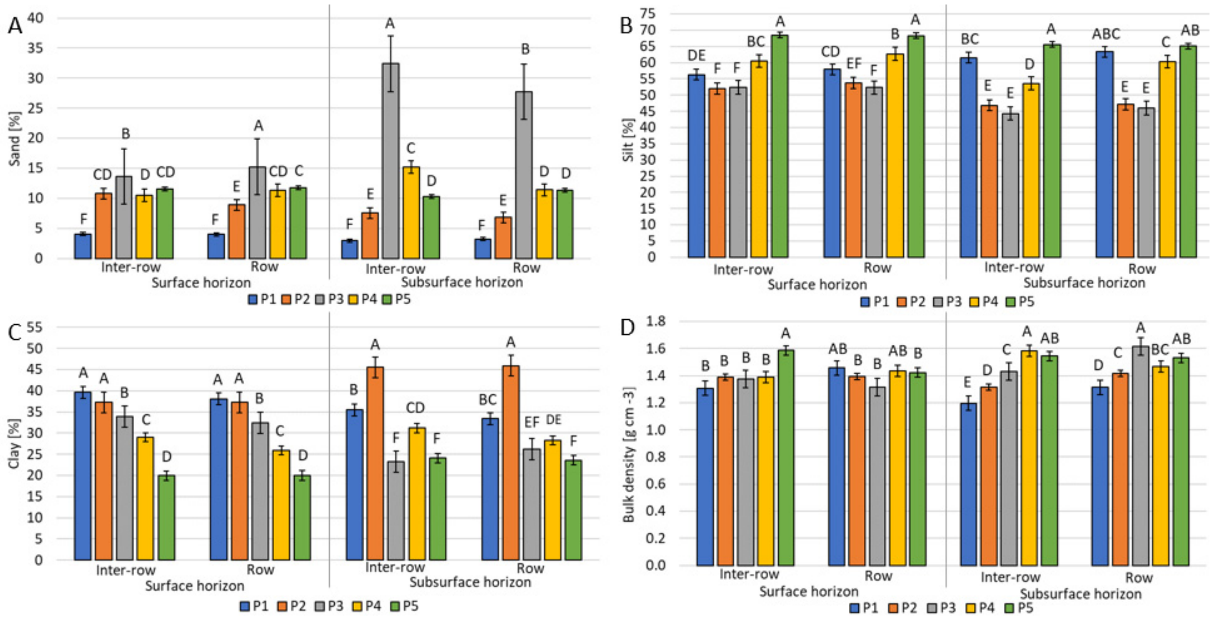

Fig. 3. Visual presentation of basic soil physical properties (sand, silt, clay content and bulk density) at the five selected slope points (P1, P2, P3 P4, and P5). Different letters assigned to positions indicate statistically significant differences between positions (P1–P5) and row / inter-row area at the same horizon.

Table 2. ANOVA table for the analyzed soil properties.

Effect		Pr > F*						
	Soil horizon	DF*	Sand content (%)	Silt content (%)	Clay content (%)	Bulk density (g cm^{-3})	pH [H_2O]	Humus (%)
SP[a]	Apg	4	**< 0.0001**	**< 0.0001**	**< 0.0001**	**0.0003**	**< 0.0001**	**< 0.0001**
	Subsurface	4	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**	**< 0.0001**
R/I[b]	Apg	1	0.4155	**0.0126**	**0.0039**	0.7821	**< 0.0001**	**< 0.0001**
	Subsurface	1	**< 0.0001**	**< 0.0001**	0.2483	**< 0.0001**	**< 0.0001**	**< 0.0001**
SP × R/I	Apg	4	**< 0.0001**	0.1909	**0.0772**	**0.0004**	**< 0.0001**	**< 0.0001**
	Subsurface	4	**< 0.0001**	**0.0003**	**0.0004**	**< 0.0001**	**< 0.0001**	**< 0.0001**

The bold values are statistically significant, [a] Slope position (P1, P2, P3, P4, P5), [b] Row/Inter-row, *DF – number degrees of freedom; *Pr > F – significance level.

highest average clay content was observed at the P1 and P2 positions, and the lowest at the P5 position. However, the difference in the clay content between row and inter-row space was observed only in the Ap horizon (*P* = 0.0039), while the difference in the average clay content in the subsurface horizon between row and inter-row space was not significant (Figure 3C). Several authors state that silt particles are more susceptible to moving down a slope than clay and sand particles (e.g., Cerdan et al., 2010; Torri et al., 1997).

Although such results of clay and sand content were not expected, they may be the result of field work, e.g., deep plowing before planting vineyards. Namely, the studied Stagnosols presumably had an increased clay content in the subsurface horizon, where deep tillage disrupted the natural profile of Stagnosol, and the illuvial horizon was mixed with the upper horizons (A and Eg) and a new horizon was developed. In Croatian Pseudogley, the vertical increase in clay content is a consequence of eluviation / illuviation of clay (Rubinić et al., 2015). Thus, after deep processing, the differences in soil structure throughout the profile, characteristic of the natural profile of Stagnosol (i.e., A-Eg-Btg-Cg), were less pronounced. Schneider et al. (2017) state that deep mixing of soil (deep tillage) disrupts the affected horizons, creating their original properties and creating a new (deeper) homogeneous layer as a combination of horizons affected by tillage.

The highest clay content at the positions of slopes P1 and P2 can also be explained because there the current surface horizon was formed by mixing the surface and the original subsurface horizon which had an increased clay content (e.g., Ziadat et al., 2010). Soil erosion caused the thinning of the original surface horizon, after which the subsurface horizon was closer to the surface. Deep plowing affected the subsurface horizon, causing an increased clay content in the surface horizon. According to Gerke and Hierold (2012), erosion leads to the removal of the topsoil, resulting in the incorporation of subterranean horizons into the surface soil by tillage. The inter-row grass cover in the vineyard after planting probably had the effect of mitigating erosion along the slope and preventing the transport of finer particles (especially clay) along the slope.

In addition to the soil texture, differences in the bulk density were also observed for slope position for both the Apg (*P* = 0.0003) and subsurface (*P* < 0.0001) horizons (Table 2). The highest values of the soil bulk density in the Apg horizon were recorded at the P5 position, while the other positions did not differ from each other. In the subsurface horizon, significantly higher values of the bulk density were recorded at lower positions of the slopes (i. e., P4, and P5) (Figure 3D). Regarding the differences in the bulk density between the row and the inter-row space, no difference was observed for the surface (Apg) horizon, while for the subsurface bulk density was significantly higher (*P* < 0.0001) in the row compared to the inter-row vineyard area. The higher bulk density in the subsurface horizon in the row of vineyards may be related to the vine root, which grows into the deeper layers of the soil in relation to the grassy inter-row vineyard area. According to Hillel (2004), root activities compress soil aggregates, roots improve aggregate stability due to excretion, death, and decay, which simulate microbial activities and humus cement production. Young (1998) states that root water uptake increases bulk density near the root due to adhesion to the soil.

Such bulk density results are expected given that the clay content is highest at the P1 and P2 positions. According to Tanveera et al. (2016), sand content showed a positive correlation with soil bulk density (r = 0.60), while clay content negatively correlated with bulk density (r = –0.41). Aubertin and Kardos (1965) discuss that the normal bulk density range for clay is 1.0 to 1.6 mg m^{-3}, and normal for sand 1.2 to 1.8 mg m^{-3}. Such a ratio of bulk density and particle size distribution of the soil can be explained by the total porosity. The upper position, P1 which has a higher clay content has a lower bulk density.

The humus content on the investigated slope is really heterogeneous and significantly different (*P* < 0.0001) with respect to the position on the slope (Table 2). The highest humus content was recorded at position P3 on the Apg and 2Cg horizons, and the lowest at position P5 (intermediate row). Statistical analysis revealed a significant difference between row spacing and row spacing (*P* < 0.0001), where a significantly higher humus content was found in the row (in both horizons) compared to the row spacing of vineyards (Figure 3B).

The higher humus content in the row in relation to the inter-row space can be attributed to the soil tillage in the inter-row space of the vineyard, which affects the faster mineralization of humus in relation to the row in which it accumulates. Hendgen et. al. (2020) in their research in the biodynamic system of vineyard cultivation found differences in the soil organic matter content between the row and inter-row space where larger amounts of SOC were recorded in the row. Molina et al. (2019) studied soil properties on slopes of different slope angles under different natural vegetation (forest, grassland) and did not notice differences in humus content between positions along the slope. Rubinić et al. (2015) also did not determine the effect of slope on humus content along sloping Stagnosol in forest ecosystem. In general, by converting natural soil to agricultural, humus content decreases over time (Haghighi et al., 2010; Kizilkaya and Dengiz, 2010), which explains the low humus content in all studied profiles.

Considering that the Stagnosol is a highly acidic soil (Husnjak, 2014; Rubinić et al., 2015), each of the investigated profiles on the slope was non-carbonate. Statistical analysis showed that the pH of the soil (in both horizons) differed significantly regardless of the position on the slope ($P < 0.0001$), where significantly the highest pH value was observed at position P1 (for Apg horizon) and P2 (for Bg horizon) (Table 2). Similar results on soil pH were obtained by Sun et. al., (2021) in a study of soil properties on sloping soils under citrus growing conditions, where they found that soil pH decreases towards lower relief positions. Differences between the soil pH in relation to the row and inter-row vineyard space were also significant ($P < 0.0001$), significantly higher pH values were observed in the interrow space (for both horizons) (Figure 4A). Kotingo (2015) obtained similar results in his research and states that the pH of the soil is higher at higher compared to the positions of lower slopes.

Water regime along the vineyard hillslope

The soil water regime at the five slope points (P1–P5) is presented in Figure 5 to Figure 9, and Table 5, which shows the range of plant available water PAW (field capacity (green line) – wilting point (red line)) in every of five slope points, and temporal variation of soil water content at sampling dates during 2019 in the Apg and subsurface horizons, and in a row and inter-row vineyard space. During 2019, no drop in soil water content was observed below the wilting point in every investigable point. In contrast, at the P3 position in the subsurface (2Cg) horizon in a row vineyard space (see Fig. 7), water content above field capacity conditions prevailed almost throughout the year. These results are not expected given that the P3 location in relation to other positions on the slope has the highest sand content (see Fig. 3A) and almost the lowest clay content (see Fig. 3C). The reason for the increased water content in the soil at the P3 and P4 positions may be the result of the accumulation of water laterally seeping over the compacted subsurface horizon from the upper positions (P1 and P2, since the positions on the slope above the P3 profile, have increased clay content in the Bg horizon, see Figure 3C). Filipović et al. (2018) studied the lateral flow of the subsoil at the eroded Haplic Luvisol with a relatively compacted C horizon. The main goal of their study was to quantify the potential for subsurface lateral flow at the pedon scale in soil profiles along hillslope. The lateral flow was hypothesized to depend on erosion-affected pedologic and spatially variable hydraulic conditions. The numerical analysis (using the HYDRUS 2D software package) suggested the occurrence of subsurface lateral flow at the sloping Bt–C horizon during summer storm events.

However, although the moisture content was above the field capacity, the relative soil moisture content was lower at P3 compared to the slope positions P1 and P2. This result may occur due to the higher sand content at the P3 slope position in the 2Cg horizon, where the sand has a lower moisture retention capacity compared to silt and clay particles.

The position on the slope has a significant ($P < 0.0001$) influence on the soil water content for the Ap and subsurface horizon (Table 3). Thus, the average water content during 2019 for the Apg horizon is significantly highest at position P1 (45.55% vol.), while at positions P3, P4, and P5 it is lowest (39.10, 40.77, 38.92% vol., respectively). In the subsurface horizon, the positions P1, P2, and P3 have significant differences between the average soil water content (45.84, 46.36, 46.74, % vol respectively), while the lowest average water content in subsurface horizon recorded at position P5 (40.39% vol.). These results are explained by the fact that a higher percentage of clay fractions was found on the upper positional slopes (e. g. P1, P2 – see Fig. 4C), which has a positive effect on water retention in the soil. Many authors confirm the positive influence of clay content on soil water retention (e.g., Al Majou et al., 2008; da Costa et al., 2013; Gaiser et al., 2000).

Statistical analysis also showed significant differences between the water content in the soil between the row and the inter-row space in the Apg and in the subsurface horizon (Table 3), wherein the Apg horizon a higher water content was recorded in the row (42.20% vol.), while in subsurface horizon on average higher moisture content recorded in the inter-row space (44.74% vol.). Interactions of soil moisture content between row and inter-row space according to the investigated positions of slopes, for Apg and subsurface horizon are shown in Figure 10. Individually by positions, the difference in soil moisture content between the row and the inter-row space in the horizon Apg was observed only for position P4, where a higher soil moisture content was recorded in the row compared to the inter-row space of the vineyard. In other positions (i. e. P1, P2, P3 and P5) no differences in soil moisture content were observed between the row and the inter-row vineyard spacing. Differences in soil moisture content in subsurface horizon between row and inter-row were observed for positions P3, P4 and P5.

Table 3. ANOVA table for soil water content.

Effect	Pr > F*		
	Soil horizon	DF*	Water content (% vol.)
SP[a]	Apg	4	**< 0.0001**
	Subsurface	4	**< 0.0001**
R/I[b]	Apg	1	**0.0139**
	Subsurface	1	**0.0395**
SP × R/I	Apg	4	**0.0004**
	Subsurface	4	**< 0.0001**

The bold values are statistically significant, [a] Slope position (P1, P2, P3, P4, P5), [b] Row/Inter-row, *DF – number degrees of freedom; *Pr > F – significance level.

Table 4. Munsell dry soil color.

Slope position/horizon		Color designation	Color description
P1	Apg	2,5 Y 6/4	Light yellowish brown
	Subsurface	10 YR 6/8	Brownish yellow
P2	Apg	2,5 Y 6/2	Light brownisch gray
	Subsurface	10 YR 6/6	Brownish yellow
P3	Apg	2,5 Y 6/4	Light yellowish brown
	Subsurface	10 YR 6/8	Brownish yellow
P4	Apg	2,5 Y 7/4	Pale yellow
	Subsurface	2,5 Y 6/4	Light brownisch brown
P5	Apg	2,5 Y 7/4	Pale yellow
	Subsurface	2,5 Y 6/4	Light yellowisch brown

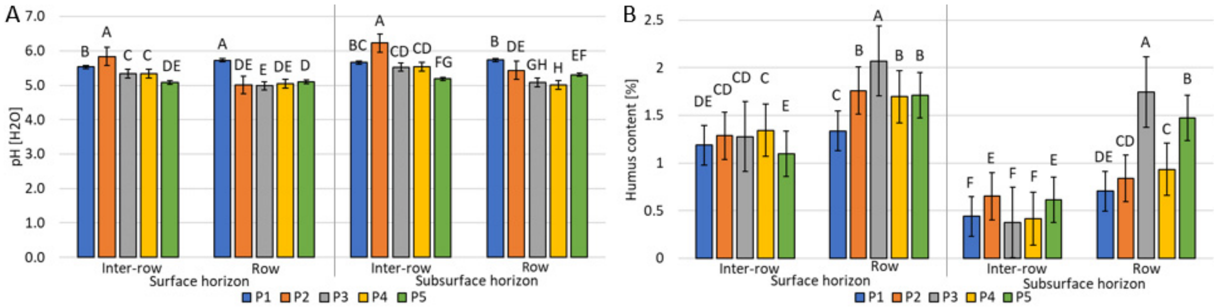

Fig. 4. Visual presentation of basic soil chemical properties (pH and humus content) at the five selected slope points (P1, P2, P3, P4, and P5). Different letters assigned to positions indicate statistically significant differences between positions (P1–P5) and row / inter-row area at the same horizon.

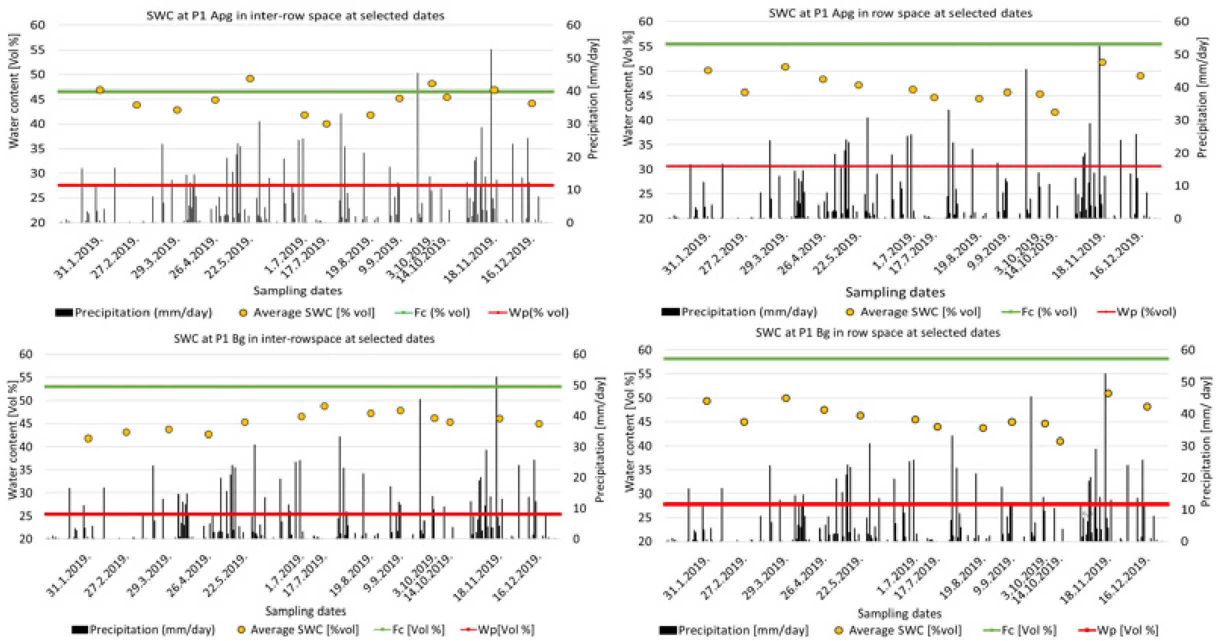

Fig. 5. Soil water content at P1 position in Apg and Bg horizons and in inter-row and row vineyard space for the year 2019.

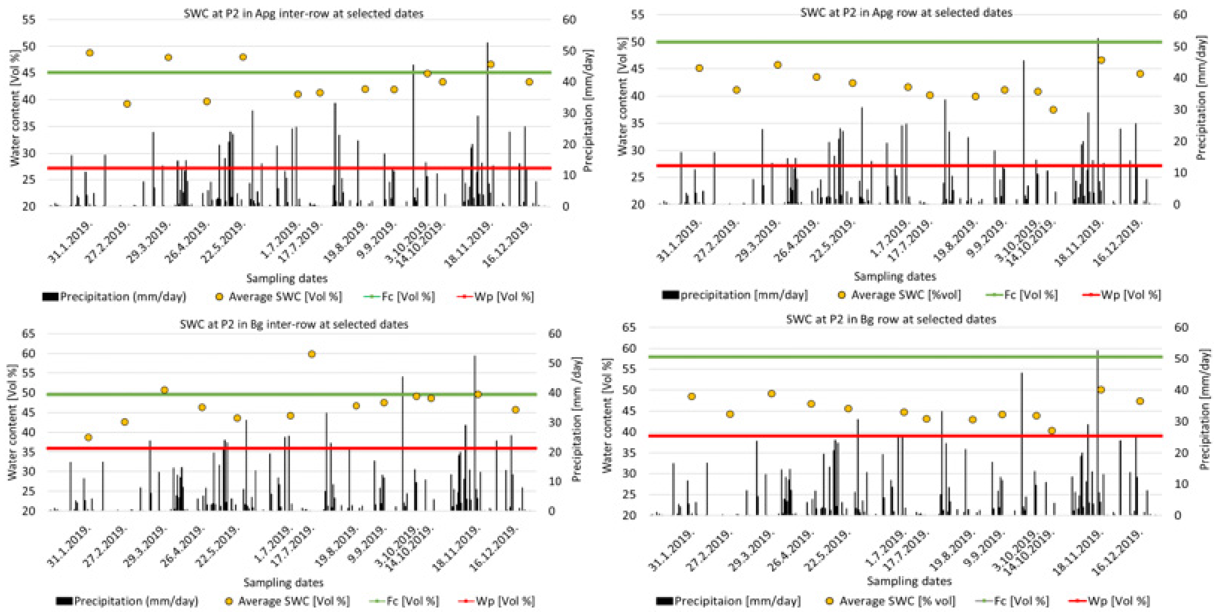

Fig. 6. Soil water content at P2 position at Apg and Bg horizon and in inter-row and row space in vineyard for 2019 year.

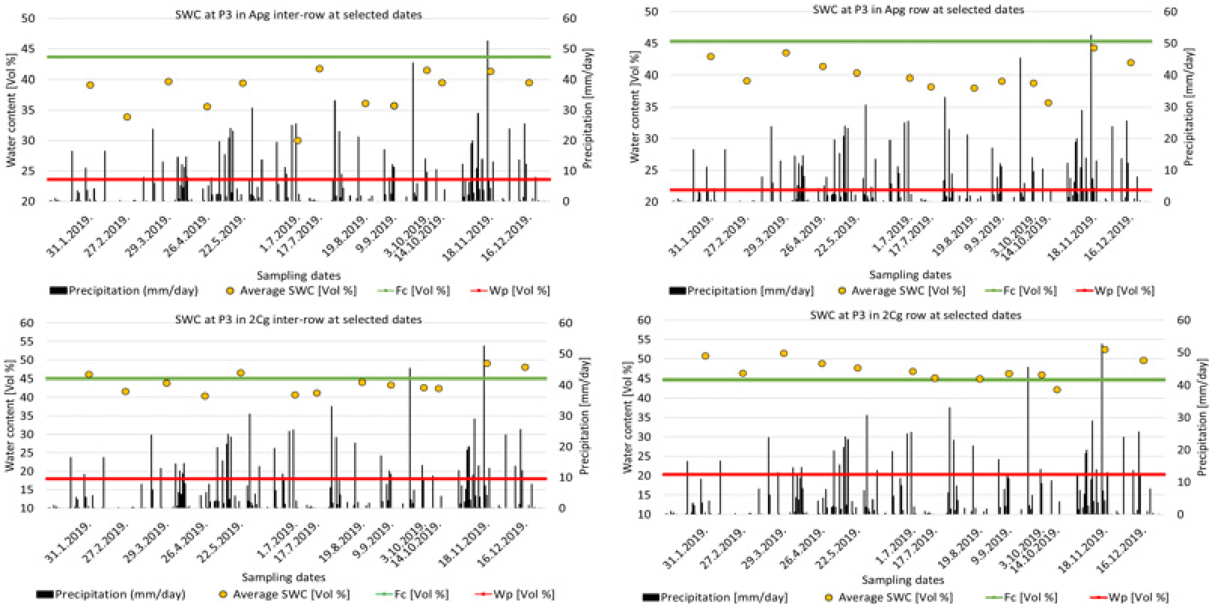

Fig. 7. Soil water content at P3 position at Apg and 2Cg horizon and in inter-row and row space in vineyard for 2019 year.

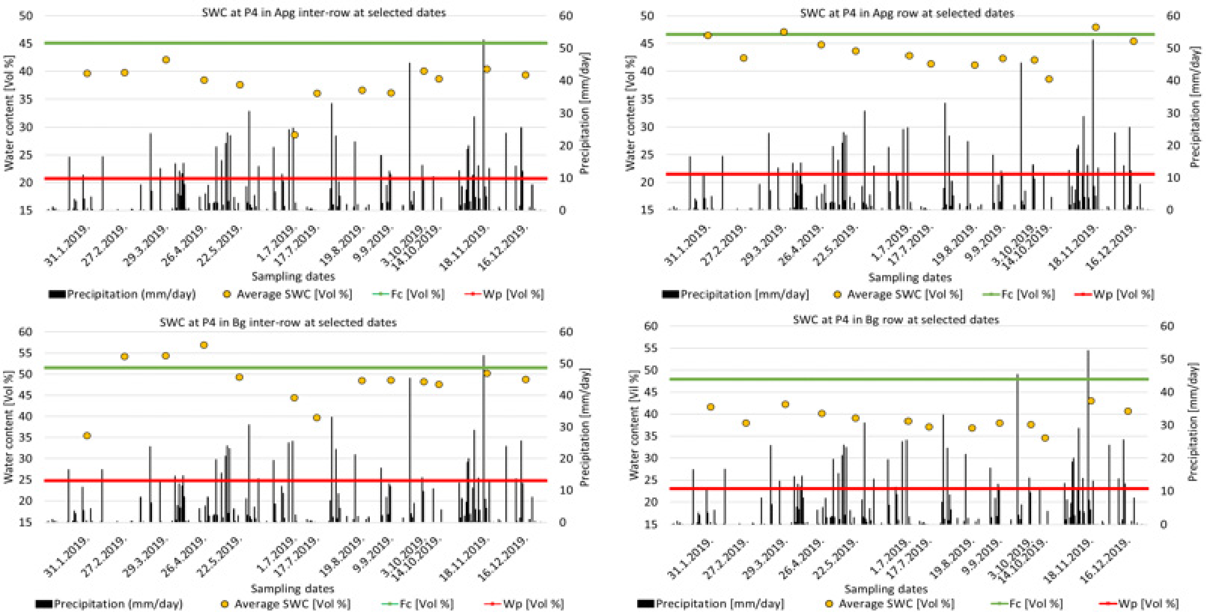

Fig. 8. Soil water content at P4 position at Apg and Bg horizon and in inter-row and row space in vineyard for 2019 year.

At positions P3 and P5 a higher soil moisture content was recorded in the row, while at positions P4 a higher moisture content was recorded in the inter-row space. Although the moisture content in the Apg horizon is statistically higher in decrease compared to the inter-row part of the vineyard (Table 3), if we look at the positions individually, we see that the difference is noticeable only for the P4 position. In the other positions, no difference in moisture content was observed between the row and the inter-row space for the Apg horizon (Figure 10).

Significantly higher soil water content between rows (for subsurface horizon) can be attributed to surface tillage which positively affects water infiltration into the deeper soil layers. Furthermore, the vine has a deeper developed root system than grass which allows it to absorb water from deeper soil layers.

Table 5. Differences between average soil water content at five slope positions in Apg and subsurface horizon (different letters indicate statistically significant differences between positions (P1–P5) at the same horizon).

Horizon	Slope position	Avegare year values of soil water content (% vol.)
Apg	P1	45.55 A
	P2	43.01 B
	P3	39.10 C
	P4	40.77 BC
	P5	38.92 C
Subsurface	P1	45.84 A
	P2	46.36 A
	P3	45.74 A
	P4	43.63 B
	P5	40.39 C

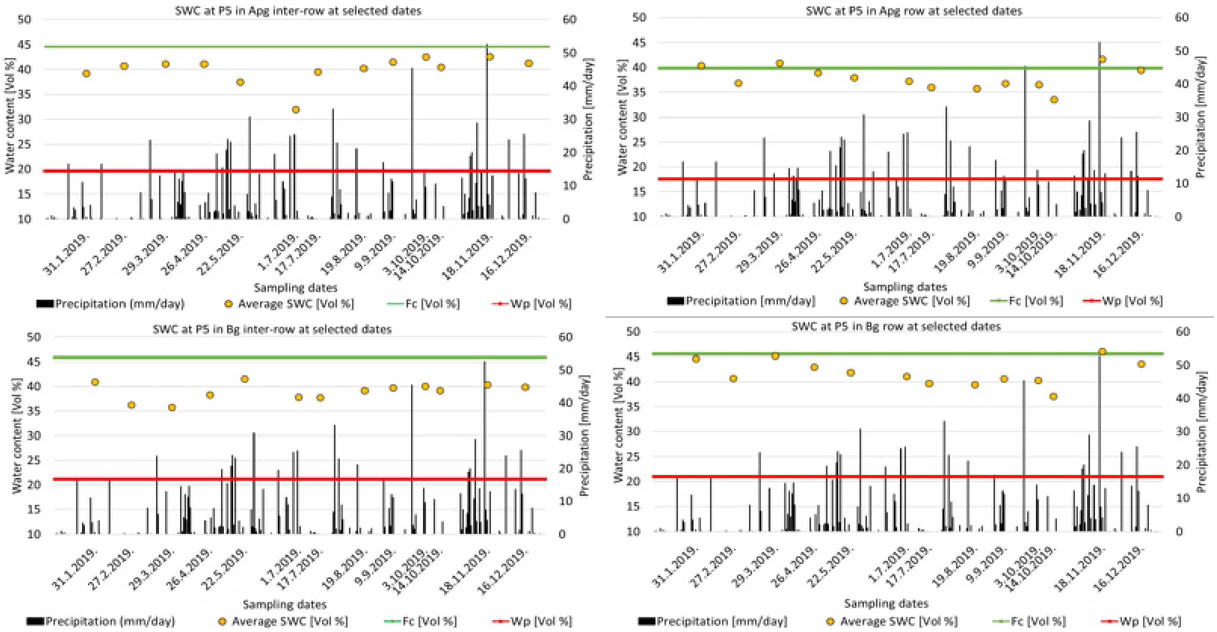

Fig. 9. Soil water content at P5 position in Apg and Bg horizons and in inter-row and row space in vineyard for the year 2019.

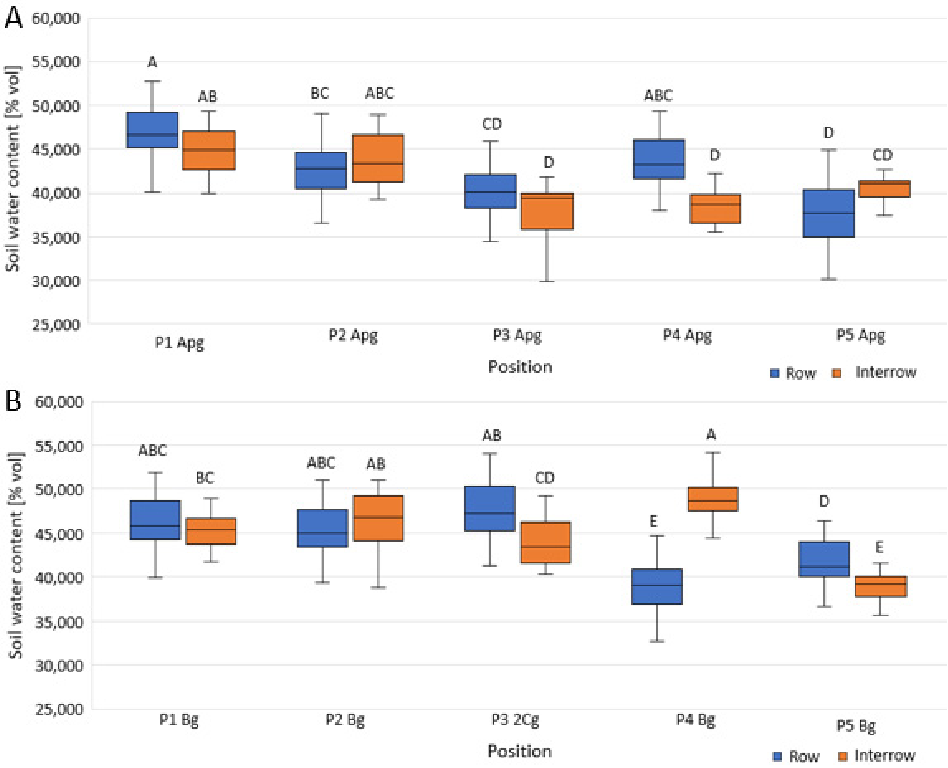

Fig. 10. Differences in soil water content (all sampling dates taken into consideration) along slope position (P1–P5) between row and inter-row space at Ap and subsurface horizon. Different letters indicate statistically significant differences between row inter-row area at the same horizon.

Smart et al. (2006) stated that up to about 80% of the vine root volume develops to a depth of 90 cm. In addition, plant root affects porosity (Kodešová et al., 2006). The root of the grass intensively absorbs topsoil water, while the root of the vine takes water from the deeper soil layers. The root system of grasses reaches a maximum density at a depth of 15 cm and disappears rapidly in deeper layers (Celettee et al., 2008). Significantly higher water content in the row in relation to the inter-row space for the Apg horizon can be attributed to the fact that almost all samplings (13 in total) were performed a few days after precipitation. The root of the vine creates larger pores (biopores) that act as a preferential flow where the water percolates into deeper soil layers (i. e. at 30 cm) faster than the inter-row space.

If a longer period until sampling had elapsed after the rain or if sampling had been carried out at a shallower depth (e.g., 10–15 cm), the water content in the inter-row space (at 30 cm) would probably have been higher than in the row space.

CONCLUSION

The aim was to test if there are any differences in soil properties and water regime regarding the slope segment and the vineyard rows (vine) and inter-rows (grass). The heterogeneity of soil properties along five studied slope positions was found to be the result of erosion and deep tillage processes before vineyard planting. Due to the deep tillage, the soil layers were mixed to a depth of about 50 cm. This caused atypical soil properties (heterogeneity of local proportions) at certain slope positions. Studies have shown that the clay content and pH are higher at higher slope positions (e.g., P1 and P2), sand and humus content higher at the P3 slope position, and silt density higher at the P5 slope position.

We determined the soil moisture regime (e.g., deficiencies or excess soil moisture content during 2019) with respect to soil properties along the slope and row / inter-row spacing in vineyard growing condition. The lower soil water content on the row space in the Apg horizon can be attributed to the influence of vine roots and surface tillage of inter-row vine space. The increased water content (above the field capacity) at the position of the slope P3 in the subsurface Bg horizon (row) indicates the possible occurrence of lateral underground flow from the position of higher slopes. However, although the moisture content was above the field capacity, the relative soil moisture content was lower at the P3 position compared to the higher slope positions. This result may be due to the higher sand content on the subterranean horizon, where sand has a lower moisture retention capacity compared to silt and clay particles. In general, although an increased moisture content was expected at lower slope positions, this was not the case in our study. Namely, it was noticed that the amount of moisture in the soil is higher at higher positions of the slope, which can be attributed to the increased clay content at the same positions.

Finally, it can be concluded that the retention of moisture on the slope is more influenced by soil properties (primarily soil texture) than the position on the slope. Slope in vineyard agricultural areas has increased in complexity due to the presence of crops and tillage which in addition to soil erosion can strongly affect soil processes.

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